Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Life-cycle assessment of cold formed steel buildings: Main influential materials and parameters

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ABSTRACT: Reducing the carbon footprint of the built environment is a duty to achieve the target of the 2030 Urban agenda. The built environment is, indeed, responsible for about 42% of of the EU total energy consumption and about 35% of the greenhouse gases emissions. One of challenges in reducing the impact of building on the environment is in quantifying them, with a good degree of accuracy. To this end, over the last decades, life cycle methodologies and metrics have been developed for the assessment of green-house gases impacts of material, products, and components, that can be applied by academics and professionals. However, the quality of the assessment relies on the quality of data related to the amount of materials used for the studied building or component, and the corresponding adopted embodied carbon coefficients. This paper aims to shed light on this two key aspects investigating the cradle – to – gate life cycle impacts of a cold formed steel building, for which high accuracy is provided in terms of amount of materials and for some of the embodied carbon coefficients. The results will provide a useful benchmark for the wider academic community in terms of environmental impacts of cold formed steel structures, which is still a under-investigated field, and shed lights on the uncertainties generated by the selection of embodied carbon coefficients.

1 INTRODUCTION

Prefab systems, also known as offsite constructions, are today at the forefront for the development of low carbon construction systems. Prefab systems includes a large family of systems that according to the level of prefabrications can be defined as stick-built (when single components are produced in factory and then assembled on site with mechanical fasteners), panelized (when full walls or floor panels are realized in controlled environment and connected together on site, and volumetric (when fully tridimensional pods, or rooms are realized in factory and brought to site to be vertically and horizontally connected). Prefab systems, after having historical mix fortune, are today widely spreading for the realization of high standards long-terms construction systems. They are indeed very often associated to new energy-efficient buildings (Gervasio et al 2018, Iuorio et al 2019). Among prefab system, cold-formed steel (CFS) construction systems are becoming popular systems for the speed of production, the quality of final products and the structural efficiency.

1.1 *The contributions of the work*

This paper aims to investigate the environmental impacts of a cold-formed steel building, discuss the main contributing components and to critically analize how the adoption of a variety

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of databases for the calculation of the embodied carbon (EC) can provide significant differences in the obtained results.

2 CASE STUDY

This research examines a CFS school built in Italy in 2009. The school comprises 6 joint one storey stick-built CFS buildings of about 4 m height. The school has been designed for a grade 2 seismic zone according to the Italian classification OPCM 2006 and was designed and built to achieve the best energy class. All walls and roofs comprises CFS components and are designed according to sheathing braced methodologies, which accounts for the collaborations between steel profiles and sheathing panels, to achieve the required racking capacity (Iuorio, 2009). All steel components (i.e. wall studs, tracks, and rafters, as well as roof joists, tracks and blockings) are made of steel grade S320, which are zinc coated and dip – hot galvanized, and have thicknesses ranging between 1.5mm to 3.0mm. The structural sheathing panels are made by 9mm thick type 3 Oriented Strand Boards (OSB). The definition of the functional "packets" and technological choices visible in Figure 1c aimed to the eco-efficiency of the building in its life-cycle, and included wood wool panels (CELENIT) and hemp fiber as thermal insulation material for walls and roof, and gypsum based panels for fire resistance. All the sections of walls and floors are discussed in detail in Iuorio et al 2023.

Figure 1. British Force School (BFS): a. general view; b. typical wall; c. external wall stratification.

3 METHODOLOGY

One of the most complete and accurate methodology for the environmental assessment of the environmental impacts of a construction system is the life cycle analysis, which can be carried out in accordance to the ISO 14040/44 standard. In this paper, a cradle-to-gate LCA methodology of the BFS school is analysed, to understand the impacts of the structural and non-structural components of a CFS building, for which the bill of material is defined with high accuracy, because retrieved by official design and construction documents. Later in section 5, the results of the LCA study for the main structural components will be compared to those attainable from a simplified approach.

3.1 *LCA of the BFS building*

In his study the LCA boundaries include only the production stage (A1–A2–A3). Modules A1, A2 and A3 are indicated as a single aggregated module which includes all the steps from the cradle-to-gate (raw material supply, transport impacts and manufacturing) of the building components adopted for the case study construction. The total GHG emissions deriving from phases A1 to A3 represent the embodied emissions of the building. The life cycle analysis is developed with the use of One Click LCA automated life cycle assessment software (One Click), according to the requirement of the (EN 15978) standard, which is in line with the (ISO 14040/44) standard. As reported in Table 1, six standard impact categories are considered in this study.

Table 1. Impact categories considered.

Impact Category	Abbreviation	Unit
Global warming potential	GWP	$kgCO_2$-eq
Acidification potential	AP	$kgSO_2$-eq
Eutrophication potential	EP	$kgPO_4$-eq
Ozone depletion potential	ODP	$kgCFC_{11}$-eq
Formation of ozone of lower atmosphere	POCP	kgC_2H_4-eq
Total use of primary energy	TUPE	MJ

According to the LCA methodology, the bill of materials has been calculated for each examined building component, and then for each material the corresponding cradle-to-gate impacts have been evaluated on the basis of the corresponding EPD, retrieved in the One Click databases.

3.2 *Life cycle inventory*

In order to analyse the environmental impact of the case study, the following Table 2 show the quantities of materials used for the walls (both load-bearing and non load-bearing walls) and roof of the BFS School, making the distinction between materials for structural and non-structural components.

Table 2. Bill of materials.

	Construction Material	Quantity (Density)	Struct./ Non-Struct.
Foundation	Concrete (12/15 MPa)	199 m^3 (2400 kg/m^3)	Non-Struct.
	Concrete (30/37 MPa)	424 m^3 (2200 kg/m^3)	Struct.
	Rebar	18.3 ton (7850 kg/m^3)	Struct.
Load-Bearing Wall	Cold Formed steel (CFS)	44.6 ton (7850 kg/m^3)	Struct.
	OSB panels	52.6 m^3 (617 kg/m^3)	Struct.
	Wood wool panels—CELENIT N 25	28 m^3 (460 kg/m^3)	Non-Struct.
	Wood wool panels—CELENIT N 50	56 m^3 (360 kg/m^3)	Non-Struct.
	Fibre-cement panels	8.9 m^3 (1850 kg/m^3)	Non-Struct.
	Gypsum fibreboard—Knauf Vidifire	106 m^3 (1180 kg/m^3)	Non-Struct.
	Hemp Fibre insulation	300 m^3 (35 kg/m^3)	Non-Struct.
Non-load Bearing Wall	Cold Formed steel (CFS)	6.4 ton (7850 kg/m^3)	Non-Struct
	Mineral fibre insulation	46 m^3 (56 kg/m^3)	Non-Struct.
	Gypsum fibreboard—Knauf Vidifire	46 m^3 (1180 kg/m^3)	Non-Struct.
Roof	Cold Formed steel (CFS)	50.9 ton (7850 kg/m^3)	Struct.
	OSB panels	45 m^3 (617 kg/m^3)	Struct.
	Wood wool panels—CELENIT N 25	126 m^3 (460 kg/m^3)	Non-Struct.
	Hemp Fibre insulation	252 m^3 (35 kg/m^3)	Non-Struct.
	Corrugated galvanized steel	2524 m^2 (13.95 kg/m^2)	Non-Struct.

4 RESULTS

Table 3 indicates the overall GHG impacts of the BFS school according to the six impact categories. The results shows that the EC of the building amounts to approximately 606 tons of

CO_2e. As shown in Figure 2, about 70% of these GHG emissions are due to the materials and quantities used in walls (load-bearing and not-load-bearing walls) and roof, while 24.1% is due to the foundations. Among the other analysed impact categories, the contribution of the materials included in the wall mainly covers the impacts quantified in EP, ODP and TUPE with percentages equal to 62%, 54% and 44%, respectively. The roof components are primarily responsible for the observed AP and POCP impacts, with percentages incidence of 47% and 51%, respectively. The foundation are primarily responsible for 24.1% of GWP and for 20% of the AP, plus about 14% on average for the remaining impact categories.

Table 3. Global LCIA results.

	GWP $tonCO_2$-eq	AP $tonSO_2$-eq	EP $kgPO_4$-eq	ODP kgCFC11-eq	POCP kgC_2H_4-eq	TUPE MJ
Total	606	1.8	370	40×10^{-3}	152	8′090′092

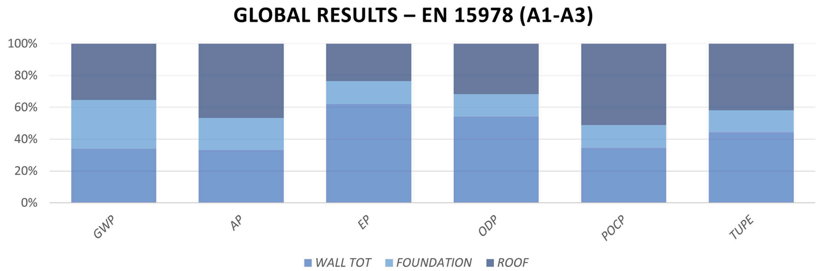

Figure 2. LCIA results: incidence percentages in each impact category.

In terms of percentage incidence of the individual materials within each building component, Table 4 and Figures 3 report the LCIA results for the foundations. The main responsible of the quantified impacts for foundations is the concrete C30/37. In terms of GWP, this material accounts for 70.5%, with about 130 tons of CO2e. The steel reinforcement for concrete (C 30/37) has the greatest impact in terms of POCP (about 31.9%) while it has a very low impact in terms of GWP and AP, with incidence percentages of 5.5% and 3.5% respectively. The Lean concrete (C 12/15) has lower impact the C 30/37 both because it is present in a smaller quantity and because it has a lower carbon factor (ECC). In particular, from the EPDs, concrete C30/37 and concrete C12/15 have emission factors of 294 kgCO2e/m^3 and 217 kgCO2e/m^3, respectively.

Table 5 and Figure 4 show the LCA results for the CFS structural walls. The structural components (CFS and OSB panels) are responsible for 9.44×10^4 $tonCO_2$-eq that correspond to 51.5% of the total GWP of the load-bearing walls. In particular, CFS profiles show a predominant EC (80%) with respect to OSB panels (20%). The non-structural building materials cause an overall EC of about 8.9×10^4 $tonCO_2$-eq. Among them, the three thermal insulation panels cause about 18.1% of the GWP of the walls. Natural hemp fiber insulation is present in greater quantities but is much more sustainable than wood wool insulation panels. Instead, the fibre-gypsum board and the fibre cement panel are responsible for 14.5% and the 16% of EC, respectively. As for the other considered impact categories, the structural CFS is the most impacting building material in terms of AP (31%), followed by the fibre-gypsum board (26.8%). In addition, the fibre-gypsum board involves 67% of the EP of the walls. In terms of ODP, OSB panels and fibre-gypsum board are the most impacting materials, with percentages of 43.8% and 30.1%, respectively. Furthermore, the insulating panels in wood wool (CELENIT N 50 and CELENIT N 25) are responsible for 30.1% of the photochemical ozone creation potential of the structural walls. At the same time, structural materials (structural CFS and OSB) account for about 43.7% (28.7% and 15%, respectively) in the POCP indicator. The materials that involve the greatest total use of primary energy are the structural CFS and the fibre-gypsum boards, respectively, with percentages of 32.9% and 25.7%. In this case, the percentage of incidence of non-structural materials is approximately 58.3%.

Table 6 and Figure 5 show LCA results for non-load-bearing walls. It is observed that, in all analysed impact categories, the least sustainable material is the fibre-gypsum board (responsible for 44.8% of the total GWP), followed by the non-structural CFS (responsible for 41.9% of the total GWP). The mineral fibre insulation panel is the most sustainable material.

Table 4. LCIA results: Foundation.

Material	GWP $kgCO_2$-eq	AP $kgSO_2$-eq	EP $kgPO_4$-eq	ODP kgCFC11-eq	POCP kgC_2H_4-eq	TUPE MJ
Structural	1.41×10^5	2.70×10^2	4.12×10	4.28×10^{-3}	1.78×10	8.6×10^5
Non-structural	4.45×10^4	9.38×10	1.23×10	1.30×10^{-3}	3.98×10	2.50×10^5
Total	1.85×10^5	3.64×10^2	5.35×10	5.58×10^{-3}	2.18×10	1.11×10^6

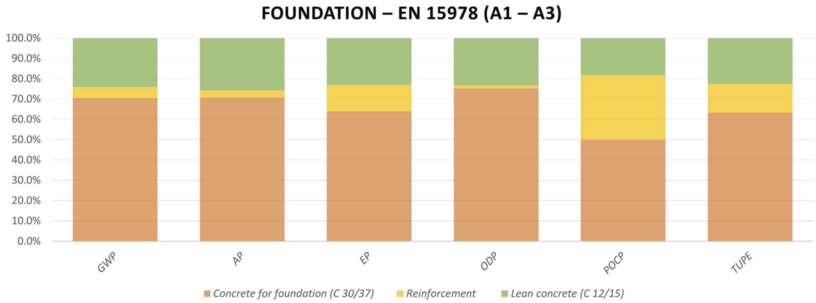

Figure 3. Percentage incidence of building materials in LCIA results: Foundation.

Table 5. LCIA results: Load-bearing Walls.

Material	GWP $kgCO_2$-eq	AP $kgSO_2$-eq	EP $kgPO_4$-eq	ODP kgCFC11-eq	POCP kgC_2H_4-eq	TUPE MJ
Structural	9.44×10^4	1.66×10^2	2.14×10	8.42×10^{-3}	2.10×10	1.29×10^6
Non-structural	8.86×10^4	3.53×10^2	1.55×10^2	1.08×10^{-2}	2.69×10	1.80×10^6
Total	1.83×10^5	5.19×10^2	1.76×10^2	1.92×10^{-2}	4.79×10	3.09×10^6

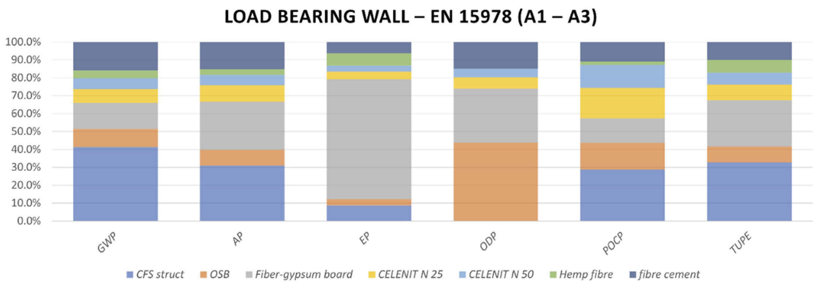

Figure 4. Percentage incidence of building materials in LCIA results: load-bearing walls.

Table 6. LCIA results: Non Load-bearing Walls.

	GWP $kgCO_2$-eq	AP $kgSO_2$-eq	EP $kgPO_4$-eq	ODP kgCFC11-eq	POCP kgC_2H_4-eq	TUPE MJ
Total	2.60×10^4	9.89×10	5.65×10	2.85×10^{-3}	5.36	5.64×10^5

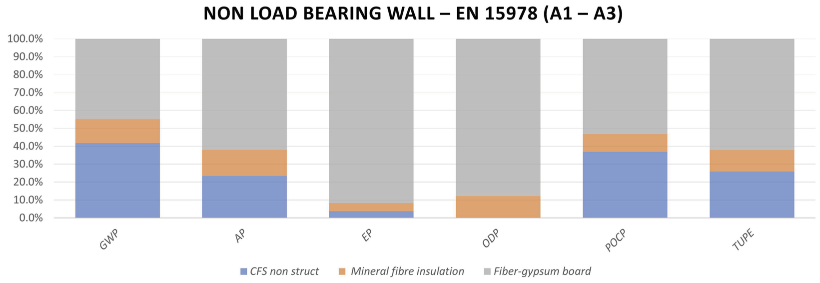

Figure 5. Percentage incidence of building materials in LCIA results: Non Load-bearing Walls.

Finally, Figure 6 shows the results for the roof. In this case, the structural components are responsible for 10.25×10^4 $kgCO_2$-eq (Table 7) and cover 47.8% of total GWP. The materials that most affect the embodied carbon are the CFS (40.2%), CELENIT N 25 (29.9%) and corrugated galvanized metal sheets (19.3%). As in the case of the walls, the hemp fiber insulation has lower impact than CELENIT N, involving just 3% of the GWP. Regarding AP, the percentages are equal to 45.1%, 26.8% and 21.8% for the corrugated galvanized metal sheets, CELENIT N 25 and CFS, respectively. In terms of TUPE, the CFS and the OSB account for 34.2% and 6.9%, respectively. Among the non-structural materials, CELENIT N 25 show a greatest impact (34.7%).

Table 7. LCIA results: Roof.

Material	GWP $kgCO_2$-eq	AP $kgSO_2$-eq	EP $kgPO_4$-eq	ODP $kgCFC_{11}$-eq	POCP kgC_2H_4-eq	TUPE MJ
Structural	10.25×10^4	2.23×10^2	2.26×10	7.31×10^{-3}	2.19×10	1.40×10^6
Non-structural	11.25×10^4	6.22×10^2	6.42×10	5.39×10^{-3}	5.59×10	1.99×10^6
Total	2.15×10^5	8.45×10^2	8.68×10	1.27×10^{-2}	7.78×10	3.39×10^6

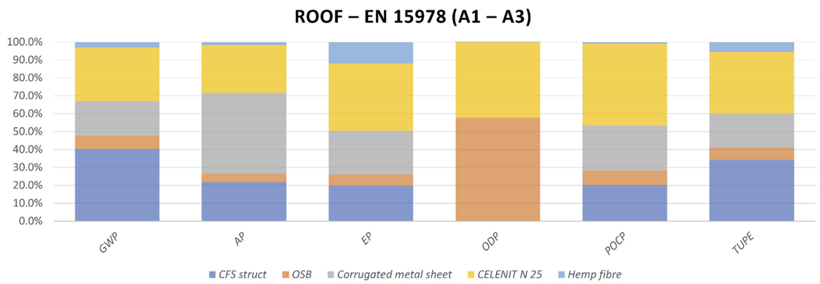

Figure 6. Percentage incidence of building materials in LCIA results: Roof.

5 COMPARISON BETWEEN DIFFERENT LCA DATABASES

As discussed the GWP is key environmental impact to evaluate the EC of a building/construction. The key variables that drive the definition of EC are the amount of material per unit of the building and the Embodied Carbon coefficient (ECC) in terms of kgCO2e per kg of material. While, as seen, the first variable is closely dependent on the analyzed project, instead the evaluation of ECC is certainly more complex, since, the environmental profiles of the materials used in constructions are rarely available. To understand how much the definition/selection of ECC can influence the total EC results, here a simplified methodology (De Wolf et al 2014) is applied for the evaluation of the EC of the main structural components/materials and for the evaluation of the ECCs, two databases, namely ICE (Hammond & Jones 2010) and AMECO were considered. In particular, the ICE has been published by the University of Bath, and presents 'cradle-to-gate' data for carbon and energy impacts of primary building materials, mainly focused on the UK market. However, since in many cases the production of energy to manufacture a process is the dominant carbon impact and therefore this data can be extrapolated to different markets with different energy sources. The database presents some of the background for the data sources enabling the user to infer data quality. The AMECO Software calculates environmental impacts of buildings and bridges made of steel and concrete. Table 8 shows the obtained results. Please note that the quantities of concrete and CFS refer only to the structural components. The quantities of OSB and rebar are the total quantities calculated for the BFS. The ECCs from the two external databases are higher in all cases, with the exception of steel. In the case of concrete, the values are highly comparable while both in the case of OSB and steel reinforcement the ICE and AMECO coefficients are more than double those from One Click LCA. Clearly these differences are reflected in the calculation of the GWP. However, the total values calculated for the structural materials considered are comparable and equal to about 328 tons of CO2e and 333 tons of CO2e respectively with the ECCs coming from One Click LCA and those provided by the two external databases. As can be seen in Figure 7, the use of ECCs from different databases leads to a different percentage incidence of structural materials compared to the total GWP they generate. In fact, according to the LCA conducted using One Click LCA (Figure 7a), steel represents the most impactful structural material in terms of GWP (51.5%), while in the second case (Figure 7b) concrete accounts for 40.3 % of the total GWP of structural materials and steel accounts for 36.1%.

Table 8. BFS: Global Warming evaluation with different databases.

Material	kg	EC (ICE/AMECO) [kgCO2e/kg]	GWP (ICE/ AMECO) [kgCO2e]	EC (One Click LCA) [kgCO2e/kg]	GWP (One Click LCA) [kgCO2e]
Steel	95500	1.24[2]	118420	1.77	169035
OSB	60219	0.99[1]	59617	0.45	27099
Concrete	1017600	0.13[1]	132288	0.12	122112
Rebar	18317	1.24[2]	22713	0.55	10074

1 Coefficients evaluated on the basis of ICE (ICE 2010)
2 Coefficients evaluated on the basis of AMECO

6 CONCLUSION

This study analyses the LC impacts of a CFS building built in Italy. The LCA is developed according to a cradle-to-gate approach, investigating the impacts of both structural and not structural components. The study demonstrates, when the building is a single story building, as for the investigated case, the GWP is nearly equally shared between walls, roof and

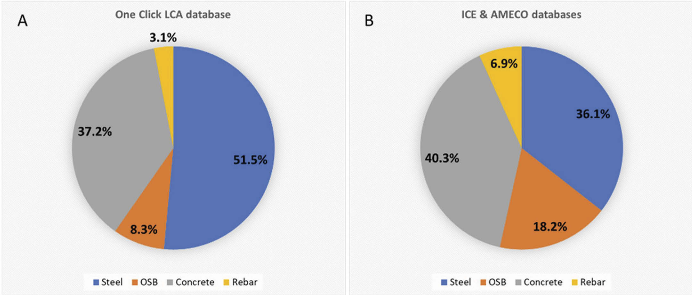

Figure 7. Percentage incidence on total structural materials GWP: a) ECCs from One Click LCA; ECCs from ICE & AMECO.

foundation (see Figure 2). But when the materials are analysed, it is clear the strong incidence provided by the CFS structural members, followed by OSB panels (for a total combined incidence of 80% of structural walls GWP). Among the insulations, the hemp fibre is that with lower incidence. While for the foundation, the impacts are primarily driven by the C30/37 concrete. Therefore, these results restates the outmost importance and necessity to optimize the structural system, and that future code allowing the dissipative design of CFS system could have a significant impact also on the environmental profile of this prefab system. Finally, section 5, shows how EC results are strongly dependent on the ECCs considered, with the simple example showing how the percentage incidence can be flipped by considering a different variety of ECC database. Therefore, the continue development of EPDs for current and future building materials will be the most appropriate approach to develop reliable assessments.

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